

Dynamical and Observable Constraints on RAMBOs: Robust Associations of Massive Baryonic Objects

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ABSTRACT

If the halo dark matter consists of faint baryonic stars, then these objects probably formed at an early epoch within large associations with similar dynamical properties to globular or open clusters. We use the luminosity function of globular clusters as a function of galactocentric distance to provide a strong constraint on the properties of RAMBOs. We show that at the solar radius, dynamical constraints confine such clusters to a bounded and narrow parameter space with effective radii between 1 pc and 15 pc, corresponding to masses between $\sim 10 - 10^4 M_\odot$ and $\sim 10^4 - 10^6 M_\odot$, respectively. We argue that gravitational microlensing is the only method capable of constraining the abundance of dark matter in the form of RAMBOs.

Subject headings: Dark matter, Globular clusters: general, Galaxy: kinematics and dynamics - halo, Stars: low mass, brown dwarfs

1. INTRODUCTION

Observational and theoretical evidence is accumulating which suggests that dark matter may be baryonic (see Silk 1994 for a review). Within the context of $\Omega = 1$ inflationary cosmology, the entire halos of galaxies such as our own could consist of baryonic matter to $\gtrsim 50$ kpc without violating primordial nucleosynthesis constraints. In the absence of a significant gaseous component (*e.g.* Moore & Davis 1994 and references within), such a baryonic component is most likely to be in the form of faint stars. The detection of gravitational microlensing from compact objects in the galactic halo has provided tantalising evidence that low mass stars may constitute a significant fraction of the halo mass to distances of ~ 30 kpc (Alcock *et al.* 1993, Aubourg *et al.* 1993). A plausible scenario for the formation of these stars is within massive clusters of similar parameters to the observed globular clusters in our halo, which collapsed at an early epoch when Jeans mass fluctuations in the density field became non-linear ((Dicke & Peebles 1968; Fall & Rees 1985; Ashman 1990). The Jeans mass can be written as $M_J \approx 2 \times 10^4 M_\odot \Omega_\odot^{-1/2} h^{-3}$ (Ω_\odot is the density parameter and h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and provides a plausible guess for the expected mass range of any large population of dark clusters that may constitute a significant fraction of the halo mass.

It has recently been shown that Jeans mass black holes cannot make up the halo dark matter (Moore 1993; Rix & Lake 1993). On the other hand, Jeans mass dark clusters provide an alternative dark matter candidate that can also account for the heating of the old disk stars without producing an overly massive central bulge as a consequence of dynamical friction, the clusters being collisionally disrupted in the inner galaxy (Carr & Lacey 1987). Wasserman & Salpeter (1994) recently proposed a scenario in which $10^7 M_\odot$ dark clusters make up 10% of the halo mass, and contain a significant fraction of neutron stars as well as low mass debris, mergers of which could provide an explanation for the frequency of gamma ray bursts. Gravitational microlensing searches are of particular interest in detecting evidence for dark clusters (Maoz 1993). However, precise predictions depend on the mass and size range adopted for the dark clusters. We shall show in this *Letter* that these parameters are tightly constrained by means of dynamical considerations of disk heating, cluster-cluster collisions, tidal heating of the clusters, and disruption of globular clusters. These four constraints lead to a bounded region in the mass – radius plane where dark clusters can survive intact to the present day. We shall refer to these surviving dark clusters as robust associations of massive baryonic objects (RAMBOs), to distinguish them from the unclustered population of massive compact (baryonic) halo objects (MACHOs).

RAMBOs would most probably consist of either low mass stars such as brown dwarfs with mass in the range $0.001 M_\odot - 0.08 M_\odot$, or faint evolved white dwarfs in the mass range $0.4 M_\odot - 1.4 M_\odot$. An unclustered population of white dwarfs has been proposed as possible halo dark matter (Ryu *et al.* 1990, Tamanaha *et al.* 1990). Current observational searches constrain the abundance of main sequence M dwarfs (*e.g.* Richer & Fahlman

1992) and of brown dwarfs (Hu *et al.* 1994). Detecting the closest stellar dark matter candidates expected in such scenarios is within reach of current instrumentation. However, if these objects are clustered, then the nearest candidates would lie much further away. The possibility of detecting both clustered and unclustered brown dwarfs with current and future infrared telescopes has recently been studied in detail by Kerins & Carr (1994). In light of our new dynamical constraints, we also re-examine the prospects for direct detection via deep infrared and CCD surveys, and discuss the role of gravitational microlensing searches.

2. DYNAMICAL CONSTRAINTS ON DARK CLUSTER PROPERTIES

2.1 Evaporation All star clusters evaporate in a finite time due to relaxation via star-star encounters. The two-body relaxation time of a cluster of mass M_{clus} can be written

$$t_{rel} = \frac{6.5 \times 10^8 \text{yr}}{\ln(0.4N)} \left(\frac{M_{clus}}{10^5 M_\odot} \right)^{1/2} \left(\frac{1 M_\odot}{m_*} \right) \left(\frac{r_h}{1 \text{pc}} \right)^{3/2}, \quad (1)$$

where N is the number of stars of individual mass m_* and r_h is the median or half-mass radius of the RAMBO of mass M_{clus} (Spitzer & Hart 1971). The evaporation timescale, $t_{evap} \approx 100 t_{rel}$ (Spitzer 1975), therefore clusters of white dwarfs with a mean radius of a parsec and of mass equal to the smallest Jeans mass, would evaporate on a timescale of order 10 Gyrs, *i.e.* the Hubble time, τ_H for $h=1$. Brown dwarf clusters of the same mass and with $m_* = 0.01 M_\odot$, would survive for over two orders of magnitude longer. In Figure 1, we show this constraint for clusters of brown dwarfs of mass $0.02 M_\odot$ and white dwarfs of mass $0.5 M_\odot$.

2.2 Tidal radii The gravitational field of the Galaxy imposes a limiting radius to a stellar cluster. If a star passes beyond this radius, it will become unbound and escape the cluster potential. If we ignore the potential difference across the star cluster, then an approximate calculation yields an expression for the tidal radius;

$$R_T = R_G \left(\frac{M_{clus}}{3 M_G} \right)^{1/3}, \quad (2)$$

where R_G is the perigalactic distance of the star cluster and M_G is the mass of the Galaxy within R_G (*e.g.* Binney & Tremaine 1987). When the tidal radius approaches the half mass radii, r_h , of the star cluster, the rate of evaporation increases rapidly and the cluster dissolves into the deeper potential. Stellar systems with $R_T/r_h \lesssim 3$ will evaporate within τ_H (Chernoff *et al.* 1986, Oh *et al.* 1994). The tidal radius increases slowly with galactocentric distance and we plot this constraint for clusters at the solar distance $R_{G,\odot}$ and $2R_{G,\odot}$.

2.3 Cluster-cluster collisions Spitzer (1958) calculated the heating effect of giant molecular clouds upon star clusters in the disk. We can use the same arguments to calculate the disruption timescale of a dark cluster due to many encounters with similar clusters. Applying the impulse approximation to a population of clusters moving on isotropic orbits with velocity dispersion σ yields a disruption timescale

$$t_{CC} = E_{bind}/\dot{E} \approx \left(\frac{0.03\sigma}{GM_{clus}r_h n} \right), \quad (3)$$

where $E_{bind} \approx 0.2GM_{clus}^2/r_h$ is the cluster binding energy and \dot{E} is the heating rate (*e.g.* Binney and Tremaine 1987). The number density n of dark clusters at large galactocentric distances R_g within an isothermal halo is

$$n \approx \left(\frac{10^7 M_\odot}{M_{clus}} \right) \left(\frac{10 \text{ kpc}}{R_g} \right)^2 \text{ kpc}^{-3}. \quad (4)$$

The cluster-cluster disruption timescale is very sensitive to the galactocentric distance since $t_{CC} \propto R_g^2/r_h$. Adopting $\sigma = \sqrt{3/2} \, 220 \text{ km s}^{-1}$, we find that this constraint gives the horizontal dashed lines drawn in Figure 1 for cluster populations at $R_{G,\odot}$ and $2R_{G,\odot}$.

2.4 Globular cluster heating In an identical fashion to cluster-cluster disruption, a population of massive halo objects will inject energy into the halo globular clusters. The fact that these systems are very old and appear spherically symmetric and undisturbed, suggests that they are not suffering violent encounters with dark clusters. The lack of a correlation of globular cluster properties, such as luminosity or concentration with galactocentric radii within the Milky Way and other galaxies (Harris 1991), also suggests that these systems are not being disrupted because the disruption timescale $t_{GC} \propto R_g^2$.

The heating rate of the halo globular clusters by massive black holes was recently calculated in detail by Moore (1993). However, several effects combine to reduce the heating rate when the perturbers are extended systems. During a direct collision between a dark cluster and a globular cluster with similar mean radii, the heating rate is reduced by about an order of magnitude over the heating from an encounter with a point-like object such as a black hole. Consequently, black holes inject considerably more energy through penetrating encounters than via encounters beyond the cluster tidal radius, whereas extended perturbers inject roughly equal amounts of energy via direct collisions as via distant collisions. Furthermore, the heating rate scales roughly as the square of the half-mass radius of the perturber. Hence if the dark clusters are both massive and extended, they might not have a noticeable effect upon the Galaxy's globular clusters.

Binney & Tremaine (1987), after Spitzer (1958), derive an analytic expression for the heating rate of open clusters by giant molecular clouds. This formula can be applied directly to the heating of globular clusters by dark clusters which gives

$$t_{GC} \approx \frac{0.03\sigma}{G} \left(\frac{M_{GC}}{r_{h,GC}^3} \right) \left(\frac{r_{h,clus}^2}{M_{clus}^2 n} \right). \quad (5)$$

For example, Palomar 5 is at a distance $R_G \sim 16$ kpc and has a core radius, $r_c \sim r_h \approx 14$ pc, and mass $M_{GC} \approx 1.5 \times 10^4 M_\odot$. If the halo dark matter were to consist of $10^6 M_\odot$ dark clusters with effective radii of 20 pc, then Palomar 5 would be violently heated to disruption within 1 Gyr. Although the halo globular clusters are approximately 15 Gyr old, we shall derive our constraint on the size and radius of dark clusters using a disruption timescale $t_{GC} = 1$ Gyr. This allows for a slow and non-violent heating of the globular clusters that otherwise might not be observationally apparent within the present day globular cluster population. As the cluster radii decrease, penetrating encounters begin to inject a significant amount of energy and the globular clusters will be disrupted on a shorter timescale. For this reason, the constraints on dark clusters are somewhat stronger when their radii are less than that of the observed globular clusters, and the constraint tends towards that calculated for black holes.

The velocity dispersion of disk stars is observed to vary as the square root of their age, a correlation which can be obtained from heating by massive black holes (LO). To obtain the required disk heating from extended objects, Carr & Lacey (1987) note that $r_h/(1 \text{ pc}) \lesssim M_{clus}/(2 \times 10^6 M_\odot)$. Such clusters would have a devastating effect upon the halo globular clusters, heating many to disruption within a tenth of a Gyr, a timescale of order the crossing time for globular clusters such as Palomar 5 whose central velocity dispersion is $\sim 1 \text{ km s}^{-1}$.

Rather than apply constraints from a specific sub-sample of low density globular clusters, we can use the fact that the disruption timescale varies as $1/R_G^2$, and look at the variation in the globular cluster luminosity function with galacto-centric distance. We shall quantify this variation by counting the fraction f_{-7} of globular clusters brighter than $M_v = -7$ within inner and outer zones of the Milky Way. This magnitude corresponds to a cluster mass of order $10^5 M_\odot$ for a mass to light ratio of 1.5. We find that for $R_G < 10$ kpc this fraction is 0.4, and for $R_G > 10$ kpc the fraction of low mass clusters increases by less than 20% to 0.5. The typical poisson errors on these numbers are $\lesssim 10\%$. The fractional differences in the numbers of low mass clusters within M31 and Virgo cluster ellipticals is even smaller than for the Milky Way. (Note that the small difference between the fraction of low mass clusters can be attributed to galactic disruption mechanisms; tidal forces, disk crossing etc., which are more effective in the inner halo.)

The mean disruption timescale from RAMBOs is over an order of magnitude smaller for the sample of distant globular clusters which have a mean distance of 4 times

the inner sample. We can therefore constrain the properties of RAMBOs by requiring that at $R_G = 10$ kpc, less than 20% of the least massive globular cluster have been disrupted by the present day. We find that within the lifetime of the observed cluster population ~ 15 Gyrs, the least massive 20% of the globular clusters (*i.e.* those with mass $M_{GC} < 5 \times 10^4 M_\odot$), would have been disrupted by the present day if $10^5 M_\odot$ RAMBOs with radius 10 pc constituted the dark matter. This constraint is in fact slightly stronger than we achieved above by considering the disruption timescales of the Palomar clusters¹. (For these calculations we took the core radius of the dark matter distribution to be 10 kpc.) Applying this result to the model proposed by Wasserman & Salpeter (1994), we find that a fraction $< 1\%$ of the galactic halo could be composed of RAMBOs of mass $10^7 M_\odot$ with internal dispersions ~ 100 km s⁻¹, an order of magnitude lower than they proposed. We therefore conclude that the observed correlation between age and velocity dispersion of disk stars cannot arise from heating by either massive compact halo dark matter objects or by RAMBOs.

3. OBSERVATIONAL PROSPECTS FOR DETECTING DARK CLUSTERS

3.1 Infrared Observations If the dark matter were clustered, then this would have important implications for the direct detection experiments currently in progress (*e.g.* Hu *et al.* 1994). The distance to the nearest cluster will be larger by a factor $(M_{clus}/m_*)^{1/3}$, but the luminosity is increased by the larger factor (M_{clus}/m_*) . This increase in flux is only useful if the clusters can be treated as point sources. For a random distribution, the closest cluster will lie at a distance $\approx 0.5n^{-1/3} \equiv 300M_6^{1/3}$ pc where $M_6 = M_{clus}/10^6 M_\odot$, and the angular size of this cluster will be $\approx 2r_{10}M_6^{-1/3}$ degrees on the sky, where $r_{10} = r_h/10$ pc. The closest $10M_\odot$ brown dwarf cluster would therefore lie about 6 pc from the sun and subtend over ten degrees on the sky. Thus a full sky survey would be necessary in order to detect the nearest halo brown dwarf RAMBO. Both of the future infrared observatories, ISO and SIRTf, are planned to take observations only in pointed mode.

Essentially all of the clusters which lie within the dynamically allowed region in Figure 1 can be treated as extended sources, *i.e.* a cluster with r_h of ~ 1 pc at 50 kpc subtends several arcseconds on the sky. The regime in which every line of sight towards the LMC contains at least one RAMBO is indicated on Figure 1 and this bisects the allowed parameter space. To the right of this line, the clusters will give rise to a general galactic background with Poisson fluctuations in intensity. To the left of this line, a certain fraction of the sky must be observed in order to find one or more clusters along the line of sight.

¹ Applying this constraint to M31, which has a higher dark matter density than the Galaxy and values of f_{-7} and f_{-8} which vary by less than 10%, yields the constraint that the halo cannot consist of black holes of mass $M_{BH} > 10^3 M_\odot$.

The region probed by IRAS and ISO lies to the right of the allowed region indicated in Figure 1 (*c.f.* Kerins & Carr 1994). The detection criterion was based on brown dwarfs of mass $m_* = 0.02M_\odot$, using an extended source sensitivity at $6.75\mu\text{m}$ for ISO for a 3σ detection from a 2 day observation. These calculations were based on the assumption that the brown dwarfs are blackbody radiators. Recent calculations by Saumon *et al.* (1994) which include updated opacities show that the emergent spectra do not resemble blackbody emission; however the location in the colour-magnitude diagram of the low mass stars does not change significantly. Brown dwarfs of the maximum allowed mass, $m_* = 0.08M_\odot$, would have an intensity an order of magnitude higher, although the evaporation constraints are correspondingly larger and the extended emission from these clusters would still not be visible by ISO. Note that Rix & Lake (1993) conclude that RAMBOs of mass $2 \times 10^6 M_\odot$ would have been detected within the IRAS point source survey. However, this result is only correct if the nearest clusters appear as point sources, *i.e.* $r_h \lesssim 0.01$ pc, a scale much smaller than the clusters considered by these authors, and clusters of this size are already ruled out by evaporation constraints.

3.2 CCD Imaging An unclustered distribution of halo white dwarfs is detectable with current instrumentation. Within 10 pc of the sun, we expect of order 40 white dwarfs from the halo, the closest lying about 3 pc away. For a halo age of 15 Gyr, an individual white dwarf luminosity would be $\sim 10^{-5.5} L_\odot$ and the closest white dwarf would have an apparent magnitude $m_B = 16.6$. The use of proper motions to distinguish between disk and halo stars will enable current searches to constrain the number of unclustered halo white dwarfs. However if the white dwarfs are clustered, then the detection of these objects becomes significantly harder. The nearest white dwarf RAMBO would have a minimum mass $M_{clus} = 200M_\odot$ and corresponding radius $r_h \sim 4$ pc, and would therefore lie at about 18 pc and have an angular size of 13 degrees. Individual stars within the cluster would have $m_B \approx 21$. Distinguishing between disk and halo white dwarfs would be extremely difficult and require extensive proper motion studies.

Observational searches are therefore limited by the low surface brightness of the clusters. One might expect to obtain images with sensitivity at best $\mu_B = 29$ mag arcsec $^{-2}$, similar to the deepest faint galaxy count surveys. Let us consider an optimum case, a white dwarf cluster of $10^4 M_\odot$ and $r_h \approx 1$ pc. This object would have a total magnitude $M_B \sim 9$, or $m_B \sim 24$ at 10 kpc. However, at this distance the cluster would cover over 1000 arcsec 2 and have a surface brightness of $\mu_B \approx 32$ mag arcsec $^{-2}$. We have plotted on Figure 1 the region currently accessible by deep CCD searches which reach a surface brightness $\mu_B = 29$ mag arcsec $^{-2}$. Very careful observations may be able to probe a small part of the allowed parameter space, especially for a halo age less than 15 Gyr, however the sky background and readout noise will prohibit a thorough investigation of the entire allowed region.

Could RAMBOs consisting of low mass stars at the edge of the main sequence remain undetected by deep CCD searches? Consider as above, a $10^4 M_\odot$ cluster of zero metallicity stars with $m_* \sim 0.1M_\odot$. Individual stars have absolute red magnitudes $M_R =$

12 (Burrows *et al.* 1994), therefore the absolute magnitude of this cluster would be $M_R = -0.5$. At 10 kpc, its apparent magnitude $m_R = 14.5$ gives rise to a surface brightness $\mu_R \approx 22$ mag arcsec $^{-2}$. Deep searches can reach $R \approx 27$, and such clusters would be detectable because of the intense diffuse light background they produce. However, if the metal abundances of the same stars were equal to the solar value, then $M_R = 18$, and the surface brightness of the cluster would be a magnitude fainter than the current detection threshold. An observational sensitivity at the K band surface brightness predicted for this cluster, $\mu_K = 21$ mag arcsec $^{-2}$, has been reached on the Keck telescope (Hu *et al.* 1994).

3.3 Gravitational Microlensing Infrared and CCD observations appear to be incapable of probing much, if any, of the allowed parameter space for dark star clusters. Gravitational microlensing is proving to be an interesting technique for determining the stellar content of dark matter halos. Although the total extent of galaxy halos is still undetermined, observational evidence suggests that the halo of the Milky Way extends to beyond the Large Magellanic Cloud (LMC) and is at least $10^{12}M_\odot$ (Fich & Tremaine 1992). Lensing experiments towards the LMC are typically sensitive only to material between the sun and typically to half of the distance to the source, *i.e.* a total of $5 \times 10^6 M_\odot$ of dark matter per square degree along the line of sight to the LMC. Most of the stars lie within 10 square degrees, although to date, only a couple of square degrees have been searched.

These statistics are interesting because if the dark matter consists of RAMBOs, the lensing results may be dominated by small number statistics since only a few dark clusters may currently lie in the field of view. For example, if the RAMBOs have mass $3 \times 10^6 M_\odot$, then the searches of Alcock *et al.* may only have $3 \pm \sqrt{3}$ clusters within the field of view. As long as most of the LMC is monitored, microlensing will be able to provide constraints on dark matter in the form of star clusters. The most massive clusters are constrained to have half-mass radii of order 50 pc, and they have angular sizes of half of a degree at 10 kpc from the sun. The smallest dark cluster, $r_h \sim 1$ pc, would have an angular size of about an arcminute, and although the microlensing optical depth would be larger within this area, the total number of stars which could be lensed is down by the same factor and the lensing event rate is identical to that of an unclustered population of stars.

All the events from one cluster would have the same net motion of the cluster, with the internal velocity dispersion superimposed, $\sigma \approx \sqrt{GM_{clus}/4r_{clus}}$, which at maximum is ~ 10 km s $^{-1}$, although within most of the dynamically allowed parameter space, clusters would have internal dispersions of order $\sigma \approx 1$ km s $^{-1}$. The lensing events from a single cluster will yield information on the mass function of the stars rather than the internal velocity dispersion of the cluster. Recovering r_h and the masses of individual RAMBOs will require $\gtrsim 10$ events per cluster and is complicated by the fact that the covering factor of these objects is close to unity. Figure 2 shows the expected distribution of RAMBOs projected onto a region of the sky 3 deg 2 , which is about equal to the maximum extent of

the LMC which can be monitored for lensing events. For this diagram we have assumed that the RAMBOs have mass $10^6 M_\odot$ and size 60 pc. This yields a number, N_{LOS} , of order one cluster for every line of sight towards the LMC, and therefore for a Poisson distribution the fraction of sky actually covered is $1 - \exp(-N_{LOS}) = 63\%$.

Recent preprints by Maoz (1994) and Bouquet *et al.* (1994) discuss the possibility of detecting the microlensing signatures of dark star clusters of mass $10^6 M_\odot$ and $r_h \approx 1$ pc as proposed by Carr & Lacey (1987). We have shown that these clusters are excluded by dynamical constraints. Furthermore, the allowed parameter space for RAMBOs (Figure 2) indicates that these systems have a large covering factor and small internal velocity dispersions, and therefore their microlensing signatures will be very difficult to measure.

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Figure Captions

Figure 1. The mass – radius parameter space within which RAMBOs can survive until the present day. Regions at the text side of the curves are excluded by the four dynamical constraints discussed in Section 2: evaporation, tidal disruption, cluster-cluster disruption and globular cluster heating are indicated by the solid, dot-dashed, dashed and dotted lines respectively. Cluster-cluster disruption and tidal disruption are sensitive to R_G and constraints are shown for clusters at the solar radius $R_{G,\odot}$, and $2R_{G,\odot}$. The evaporation constraint is shown for brown dwarf clusters with $m_* = 0.02M_\odot$, and white dwarf clusters with $m_* = 0.5M_\odot$. The region where the number of clusters per line of sight is larger than unity is indicated and bisects the allowed parameter space. Clusters to the right of this region give rise to a galactic background with Poisson fluctuations in intensity. IRAS and ISO extended sky surveys can only detect brown dwarf clusters to the right of the

indicated lines. Similarly, deep CCD observations can only detect clusters of white dwarfs outside of the dynamically allowed region.

Figure 2. A random realisation of the distribution of RAMBOs projected onto a 3 deg^2 region of the sky, similar to the maximum extent of the LMC. We have assumed a number density of RAMBOs given by equation (4) with individual mass $M_{clus} = 10^6 M_\odot$ and $r_h = 60 \text{ pc}$. Each line of sight is expected to contain a single RAMBO on average, therefore the covering factor here is 0.63.